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THE RECORDING OF EARTH CURRENTS

by

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1. Introduction

The earth current system in use at the University of California, Berkeley, and the basis for its design are described in this report. The system is used in crustal studies by the telluric and magnetotelluric methods and in research on dynamics of the magnetosphere.

At the present time, earth currents are being investigated extensively throughout the world for the purpose of obtaining a better understanding of the origin of micropulsations, and hence indirectly for a study of solar-terrestrial relationships (e.g. Hopkins 1960, Westcott 1960, Westcott and Hessler 1960, Barsukov and Troitskaya 1961, Vinogradov 1961, Garland 1962, Kebuladze and Kiziriya 1962, Bostick and Smith 1962, Srivastava, Douglass and Ward 1962). Most stations simultaneously record magnetic field components also, so as to obtain a full record of the micropulsation variations.

This basic research is in contrast to the commercial application of telluric currents as originally applied by Schlumberger (1939) and later modified by the French geophysicists (Migaux 1946, 1948, 1951, 1952, Boissonas and Leonardon 1948, Beaufils 1950, Baranov 1951, Mainguy and Grepin 1953, Kunetz 1954 and 1957, Utzmann 1954, Lefevre 1957, Ultzmann and Favre 1957) and to a lesser extent by others (Dahlberg 1945, Rikitake 1951, Tuman 1951, Bondarenko 1955, Khovanova 1955, Porstendorfer 1955, Zagarmistr 1959, Yungul 1962).

Telluric currents are of general interest to the exploration geophysicist because they constitute a deep probing resistivity survey with the current electrodes located essentially at infinity. Telluric instrumentation is simpler to use and easier to install than deep probing resistivity equipment. In this application the range of interest extends from the surface of the earth to the basement.

Telluric currents are also monitored when the magnetotelluric method is used; this method requires measurement of orthogonal $\vec{E}$ and $\vec{H}$ field pairs in the "micropulsation" band, i.e. 1 to 1000 seconds period. Appropriate computation leads to plots of ground impedance versus period. These plots may, under idealistic conditions, be interpreted in terms of simple layered structures.

While telluric currents are useful in the above applications, they may be a hindrance to conduct of prospecting surveys involving potential field measurements. Induced polarization and magnetic surveys are

particularly affected when conducted near the auroral zones where geomagnetic activity is most pronounced. However, Westcott (1960) notes that high latitude areas, e.g. Alaska, are ideal places to convert this disadvantage to an advantage; natural field rather than artificial field electrical surveys are then preferred because of the large amplitudes, regular occurrence, and broad frequency spectrum of telluric currents.

In summary, telluric currents are used in three ways:

(1) As a means of monitoring the interaction between the solar plasma and the earth's main magnetic field (Ward, 1962a & b).

(2) As a probe for subsurface conductivity inhomogenieties in the search for petroliferous and metalliferous structures (Douglass, 1962).

(3) As part of the probing system used in magnetotelluric soundings (Cagniard 1953, Srivastava, Douglass and Ward 1962).

2. Considerations in Design of an Earth Current System

In the design of earth current recording systems, serious consideration must be given to the following inherent problems.

1. Electrode stability.
2. Electrode contact resistance versus recorder input impedance.
3. Placement and insulation of connecting leads.
4. Elimination of extraneous signals and selection of recording bandwidth.
5. Recorder sensitivity and range.
6. Timing system.
7. Recording medium and techniques of data analysis.

The nature of each of these problems is described below.

1. Electrode Stability

The electrodes are, perhaps, the most critical components of an earth current system for which a high degree of sensitivity and accuracy is demanded. For a pair of electrodes used to measure an earth potential correctly, each must be in the same stable chemical environment. Otherwise, extraneous potentials will arise that may be a function of time and therefore a source of "noise" relative to the signal sought. Since thermal instabilities are usually coupled to chemical instabilities, the former may be another source of noise. Finally, fluctuations in moisture content of the soil in which the electrodes are placed may also lead to noise.

While conventional "non-polarizing" porous pot electrodes minimize the drift problem (Jakosky 1950), their design needs to be considered carefully as we shall show subsequently.

2. Electrode contact resistance and recorder input impedance

The contact resistance of the electrode with the ground should be low compared with the total circuit resistance, so that the measuring system does not load the earth circuit. Furthermore, current should not flow through the electrodes, otherwise electrode noise or drift will result from polarization.

3. Placement and Insulation of Connecting Leads

To minimize inductive pickup in the loop formed by the ground return and the long wires connecting the electrodes to the recording system, some permanent stations bury the connecting wires. This procedure is especially important where the contact and ground resistances are extremely low. For movable field stations, however, such a procedure presents logistical difficulties, and we have found

it unnecessary for the frequency range of interest to us (1 sec period to 10,000 sec period). On the other hand, if the connecting wires are laid out above ground, then wind, moving them in the earth's main magnetic field, will occasionally produce spurious voltages, usually of a high frequency (e.g. one second period).

The insulation on the wires must be excellent, otherwise a complex electrode system will be in contact with the earth.

4. Elimination of extraneous signals and selection of recording bandwidth

There is a natural division in sources of natural electromagnetic energy at approximately one second period. At periods shorter than this, i.e. above a frequency of 1 cps, the energy arises largely in atmospheric discharges (Jewell and Ward 1962) while at periods longer than this the source is largely in interactions of the solar plasma and the earth's main magnetic field (Ward 1962 a & b). A pronounced minimum in the energy density spectrum occurs at about 1 cps (Campbell 1959) although the frequency of this minimum varies slightly with time.

We decided upon a short period limit of one second partly on the basis of the natural division of predominant source types, but also because instrumental techniques tend to differ on either side of this point. For periods longer than one second there are many paper chart recorders available with a one second response time, i.e. a one second period cutoff. While these recorders contain filters to reject artificial sources such as 60 cps signals from power transmission lines, we find it desirable to aid this rejection with an external filter.

The long period, i.e. low frequency, limit is frequently chosen to elimate events of period longer than 200 seconds to facilitate study of micropulsations (Hopkins 1960). Sometimes the bandwidth from one second period to 1000 second period is studied by variable narrow-band equipment (Smith, Provazek, and Bostick 1961).

A disadvantage of broad bandwidth is that very long period events tend to have large amplitudes so that a reduced sensitivity is normally employed when recording events of all periods greater than one second. For studying diurnal variations, bays, and magnetic storms, a reduced sensitivity is adequate. Most magnetic observatories vary the sensitivity as required. (Rooney 1939).

On the other hand, a disadvantage of limited bandwidth recording is that input signals are distorted by "ringing" of the circuits. In the

extreme, with narrow-band equipment, a single pulse input might be displayed as a damped sinisoidal oscillation in the output. It is entirely possible that misinterpretation of geomagnetic phenomena can result through use of narrow-band equipment (Ward 1962 a & b).

For the latter reason, we have utilized a sharp cutoff only near 1 second period, and a flat response for all other periods. High sensitivity has been obtained through use of automatic bias stepping as will be described subsequently.

5. Recorder Sensitivity and Range

In middle latitudes, the amplitude of micropulsation events, of periods from one second to 100 seconds, range typically from 1 to 10 millivolts per kilometer, although radical variations from this range do occur. A recorder with a sensitivity of 10 mv full scale on a six inch recording chart is satisfactory, provided potentials are measured over a distance of the order of one kilometer. Potential spreads of this order are customary for both petroleum exploration and basic geomagnetic research, but are unsatisfactory in mining exploration. Hence a recorder sensitivity of 1 mv for a full scale deflection is desirable for this latter endeavour so that potential spreads can be reduced to the order of 100 meters.

With 10 mv full scale sensitivity, scale expansion is necessary to facilitate recording of peak amplitudes of the order of 100 mv./km. This scale expansion can be achieved simply by means of automatic insertion of a bias voltage when the recording pen reaches either side of the chart, so that the pen returns to the centre of the chart. This process is referred to as automatic bias stepping in this paper.

In high latitudes, reduced sensitivity can be tolerated since the mean micropulsation activity may average 300 to 400 mv per km (Hessler and Wescott, 1960). On the other hand, in low latitudes, higher sensitivity is normally required.

6. Timing

The correlation of events between two or more stations, for periods as short as one second, demands a timing accuracy of one-tenth second. However, signals near one second period occur infrequently and are of very low amplitude (typically 0.5 mv/km maximum amplitude in middle latitudes). Pronounced signals occur frequently with periods of about 5 to 8 seconds and longer. To correlate the latter events, a timing accuracy of one second is adequate. This accuracy can be secured readily if the

recording chart drive employs a synchronous motor operated from frequency - stabilized mains. The chart paper is then transported at a constant rate. Minor frequency drifts in the power lines can be expected to lead to relative timing errors of less than one second for all stations operating from one linked power line system. Absolute timing is achieved by radio reference to the U.S. National Bureau of Standards station WWV when required.

7. Recording medium and techniques of data analysis

Regardless of the purpose of our studies of earth currents, we will want to describe the ellipse of polarization of the $\vec{E}$ field vector, if we are to follow recent practice. Hence, we may wish to describe the telluric ellipse as a function of frequency or alternatively as a pertinent parameter of the $\vec{E}$ field over a single given bandwidth. We may then use some form of X-Y plotter to obtain this information.

Alternatively we may wish to record the $\vec{E}$ field as a time series in each of two orthogonal directions. Usually these directions are astronomic north-south and east-west. From these latter recordings we can then compute the properties (i.e. ellipticity and direction of major axis) of the telluric ellipse as a function of time.

To facilitate subsequent analog filtering, the use of magnetic tape as the recording medium is sometimes advisable. Alternatively, we may digitize the data and effect digital filtering as required. The latter approach is more flexible and hence we have adopted it.

Our choice of recording on paper charts stems from a desire first to have the information available in a readily assimilated analog form, and second to avoid the high cost of high-fidelity analog or digital magnetic tape recording.

This choice of medium then dictates the chart speed since we wish to digitize the data by hand with available semi-automatic devices. All subsequent data processing may then be accomplished in digital form.

Direct digital recording has the disadvantage that the quality and character of the data is not evident during recording so that selection of data intervals prior to computation is not conveniently achieved. Additionally, digital recording equipment is not, in general, as inexpensive as analog recording equipment.

Ideally one might wish to monitor earth currents most of the time with analog equipment then insert parallel digital equipment when interesting events occur. This approach is not apt to be feasible with

with portable prospecting equipment.

We might, of course, depart from current practice and record a differential input from a pair of in-line dipoles. Such a technique may be especially suitable for mining exploration. Then the problem of determining the telluric ellipse does not exist, and in fact no subsequent data analysis is necessary. The gain ratio of the two inputs for zero output of a null bridge would be a measure of relative resistivity between the two pairs of electrodes.

However, for the purposes of our present research, we have chosen to record voltages from two orthogonal pairs of electrodes.

3. Description of System

The system as operated in the field is illustrated diagrammatically by Figure 1 and photographically by Figures 2 and 3. Our solutions of the problems under section 2 above are as follows.

1. Electrodes

A cross section of an electrode is shown in Figure 4. The basic construction consists of a pure (99.99%) copper rod inserted in a gelled solution of saturated copper sulfate in a porous cup container (Braun-Knecht-Heimann-Co No. 24420 size 4). The electrode is insulated and waterproofed at the top, where attachment to the line wire is made by soldering.

The choice of a Cu-$CuSO_4$ non-polarizable electrode is to some extent arbitrary. A Cd-$CdCl_2$ non-polarizable electrode, also gelled, exhibits about the same temperature stability, as Figure 5 illustrates. Note that both non-gelled Cu-$CuSO_4$ and Cd-$CdCl_2$ are inferior electrodes from a temperature stability viewpoint. The gelled Cu-$CuSO_4$ electrode is considered adequate since temperature differentials of 2 or 3°C, between two electrodes placed 2000 ft. apart, leading to drift potentials of the order of 0.1 mv, are unlikely to be exceeded when these electrodes are placed six to eight feet beneath the surface. A typical electrode emplacement is shown in Figure 6.

A small amount of light soil and additional copper sulfate solution are poured around an electrode lowered down an augured hole, the top of which is covered with a plywood disk and heaped over with soil. Temperature and moisture stability prevails at the bottom of the hole, after about 48 hours, as is evidenced by a drift check on the electrode. The drift check is conducted by placing two shorted electrodes at the bottom of holes situated less than six feet apart and recording the electrode output (unshorted) at intervals. Since no significant electrically driven potential is likely to exist over so short a distance, any observed potential may be attributed to chemical disequilibrium at the electrodes and is an indication of the relative instability of the pair. To support this opinion we offer the evidence of Fig 7 based on the placement of two Cu-$CuSO_4$ electrodes in pure silica sand saturated with $CuSO_4$. Stability, to the degree required (0.1 mv), is large reached within ten hours, despite a gross initial instability.

It is extremely difficult, if not impossible, to measure the relative

drift of an electrode pair placed 2000 feet apart since drift and long period earth current fluctuations are indistinguishable. Hence our recourse to the drift check described.

2. Electrode contact resistance and recorder input impedance

The potentiometric recorder in use is the Varian G-22 dual channel servo-feedback recorder. The manufacturer specifies that at 10 mv. full scale sensitivity the input impedance is essentially infinite at balance. Thus for the slowly varying earth current signals usually experienced, the recorder does not load the ground.

However, the recorders tend to exhibit drift and a wide deadband when the load resistance exceeds 125,000 ohms (100,000 ohms according to manufacturer's specifications). Since we have inserted, as part of a filter, 100 K ohms in series with the ground, it has been necessary to ensure that the combined ground and contact resistance do not exceed, say, 5000 ohms. We lowered electrode contact resistances, by situating the electrode in soil saturated with $CuSO_4$, to values in the range 500 to 2000 ohms. These values are measured across an electrode pair placed 2000 feet apart. The measurement of this resistance by ohmmeter, however quickly done, upsets the equilibrium of the electrodes so that drift occurs subsequently.

The copper sulfate used to lower the contact resistance also leads to instability for some time and it probably is on this account that better than 48 hours is required for electrodes to reach equilibrium.

Any accidental contact with the ground, other than via the non-polarizing electrodes, drives the latter to temporary disequilibrium and so must be avoided.

3. Connecting Leads

Electrode pairs are placed 2000 feet apart along orthogonal directions, usually astronomic North-South and East-West as in Figure 1. Two of the electrodes, for example south and west of Figure 1, may be replaced by a common electrode for convenience. It is customary, but not essential, that the north and east electrodes are positive with respect to south and west.

Number 18 stranded copper wire with light plastic insulations has been found to be satisfactory for the lines. Great care was taken to avoid ground loops in the overall circuitry, since if they exist, they cause the measurement of potentials between a polarized grounding terminal of the power system and a non-polarized electrode. For this reason it is

essential that the input terminals of the recorder are floating.

4. Elimination of extraneous signals

A four-section, low-pass filter has been introduced particularly to provide 60 cps rejection, but also to provide a sharp cutoff at 1 cps where the change-over in predominant energy source occurs. For the most part, the rejection of sferic energy above 1 cps has been satisfactory, although the records become noisy during local thunderstorms. The frequency response of the system, i.e. recorder plus internal filter, is shown in Figure 8.

The Varian G-22 recorder will drift, offset, or record in error if excess 60 cps signal is applied to the input. Hence, an internal filter is an integral part of the input stage. However, we have found it desirable to augment this internal filter when measuring earth currents by addition of the four-section low-pass filter referred to earlier.

A block diagram of the recorder is contained in Figure 9 while the low-pass filter is shown in Figure 10. A high pass filter with a 20 minute time constant may be inserted in front of the low pass filter if a band pass of 1 sec period to 1000 sec period is required (see Fig 10).

5. Recorder Sensitivity and Range

The 10 mv full scale sensitivity of the Varian G-22 recorder is adequate, provided 2000 foot dipoles are used for measurement of potentials.

To extend the range of the instrument, and yet retain the 10 mv sensitivity, we have utilized a modification of a bias stepping network developed for other purposes by Varian Associates. The bias circuit is shown in Figure 10 and the activating or stepping circuit is shown in Figure 11.

The bias stepper increases the range of the recorder, without decreasing sensitivity, by automatically adding or subtracting steps of voltage bias to keep the recording pens on the chart. Whenever a pen reaches either end of its travel, a limit switch closes in the recorder, energizing a stepping relay which moves a wiper across a voltage divider. The voltage divider consists of 14 resistors, 49.9 ohms each, in series with a 30 K ohm potentiometer and a 1.34 volt mercury cell. The setting of the 30 K ohm potentiometer may varied and locked so that any given voltage increment may be established across the 49.9 ohm resistors, i.e. in series with the signal. Usually this d.c. voltage increment is established at 6.0 mv. so that when a pen travels off scale in one direction it will immediately return to 60% of full scale in the other direction. The

response time of the stepping is governed by the response time of the recorder (one second).

The basic stepping circuit referred to above operates adequately under most conditions. However, if a very rapid large change occurs, sufficient to drive the recorder two scale lengths instantaneously, the stepping relays will not have time to complete their action, on the first off-scale drive, in order to effect the second range change. Hence an interruptor circuit is necessary and is illustrated schematically in Figure 11. The interruptor opens the stepping circuit so that the stepping relay may be actuated as many times as necessary to follow an off-scale signal.

In detail, 117v A.C. is converted to 20v D.C. by the power supply (Fig 11). Whenever a limit switch is closed, 20v appears at one of the stepping relay coils and also at the input to the interruptor. The 1N2071 diodes in the input provide an "on" function, that is the interruptor is turned on when any limit switch is closed, but the four relays remain isolated from each other by the high back impedances of the 1N2071 diodes.

The interrupter consists of a filter for the D.C. power, and a standard multivibrator circuit which turns a power transistor (2N154S) on and off at about 2 cps. A driver (2N241A) is used for isolation so that the 2N154S does not load the multivibrator heavily. As the power transistor is turned off and on, its corresponding relay coil becomes energized and de-energized, thereby moving the stepping switch to change the bias in the bias circuit.

The F-2 diodes across the stepping relay coil prevent high voltage transients when the coils are de-energized. The F-2 diode in the 2N154S circuit merely provides a small voltage drop to reduce the current in the off condition.

The choice of 2 cps as the operating frequency of the multivibrator is arbitrary, and may be altered by replacing the 6 μfd coupling condenser in the multivibrator circuit. However, there seems to be little point in allowing for more than two bias steps per second since the full scale response of the recorder is one second. Most natural phenomena are readily handled by this stepping speed.

There are two complete filter and bias stepper units, one for each of the two channels. The channels are coded red and blue on the schematics of Figures 10 and 11 corresponding to red and blue ink traces on the

chart paper.

Manual step switches are paralleled with the limit switches for testing and calibration.

6. Timing

The constant rate of paper transport provides a primary timing system. Additionally, the red channel contains a circuit that adds momentary bias for a few seconds every five minutes. A timing motor drives a cam which actuates a microswitch completing a bias circuit in the red channel input to the recorder; the charge on a 100 $\mu\mu$fd condenser is applied to the input. This secondary timing system is provided as a backup in the event that the paper transport of the recorder jams or slips. A manual switch parallels the timer microswitch for manual fiducial marks; this simple mechanism is used to insert WWV times on the charts.

7. Recording medium and techniques of data analysis

A paper chart speed of 1/2"/minute is often employed so that an 80 foot roll of chart paper will last longer than 24 hours (in fact, it lasts 34 hours). The chart paper employed (Varian type 4A) is printed with 10 divisions per inch along the time axis, thereby permitting convenient digitization only at 12 second intervals, or with added effort at 6 second intervals (every half division).

Thus the shortest period for which we may compute power density corresponds to the Nyquist frequency (Blackman and Tukey 1958)

$$f_{max} = \frac{1}{2\Delta t} = 0.0833 \text{ cps } (12 \text{ seconds period})$$

where Δt is the data sampling interval. Power density spectra and coherency spectra are computed digitally to facilitate analysis of the nature and origin of the signals studied (Ward 1962 b).

For a higher Nyquist frequency we must reduce the data sampling interval, which in turn demands a higher chart speed. Thus we frequently use a chart speed of 1"/min and a sampling interval of 3 seconds. The telluric station requires attention twice a day, for change of chart roll, when operating at this latter chart speed.

Regardless of which of these two speeds we use, however, the band between our filter cutoff (1 cps) and the Nyquist frequency will alias below the Nyquist frequency. Referring to Figure 12, the effect of sampling a high frequency event at infrequent intervals is to make the event appear of lower frequency.

While there is seldom much energy density between the Nyquist frequencies we have selected and the filter cutoff, we can alway reject this aliasing band by digitally prefiltering the data prior to power density and coherency computations if necessary.

We usually obtain the telluric ellipses directly from the records, without recourse to digitization. The scatter in the direction of the major axis and the ellipticity of the ellipses is sufficiently great, however, to demand more sophisticated treatment. Smith, Provazek, and Bostick (1961) have employed narrow band filtering about spectral peaks prior to determining the field ellipses and thereby minimized the scatter. We propose to use zero-phase-shift digital filters centred about coherency peaks, to accomplish the same objective. The more flexible digital filters can be designed to eliminate spreading of a single pulse over a substantial time interval, whereas realizable analog filters always "ring" because of the inseparability of high Q and narrow band with analog devices.

4. Typical Signals Recorded

Typical signals recorded with the system described above are presented in Figure 13. The East-West component (E_y), recorded on the red channel, is offset 1/10" relative to the North-South component (E_x) recorded on the blue channel. The offsetting permits pen overlap.

Timing always refers to the position of the E_x (blue) trace and hence timing of events on the E_y (red) trace must take account of this offset (6 seconds offset for chart speed of 1"/min.)

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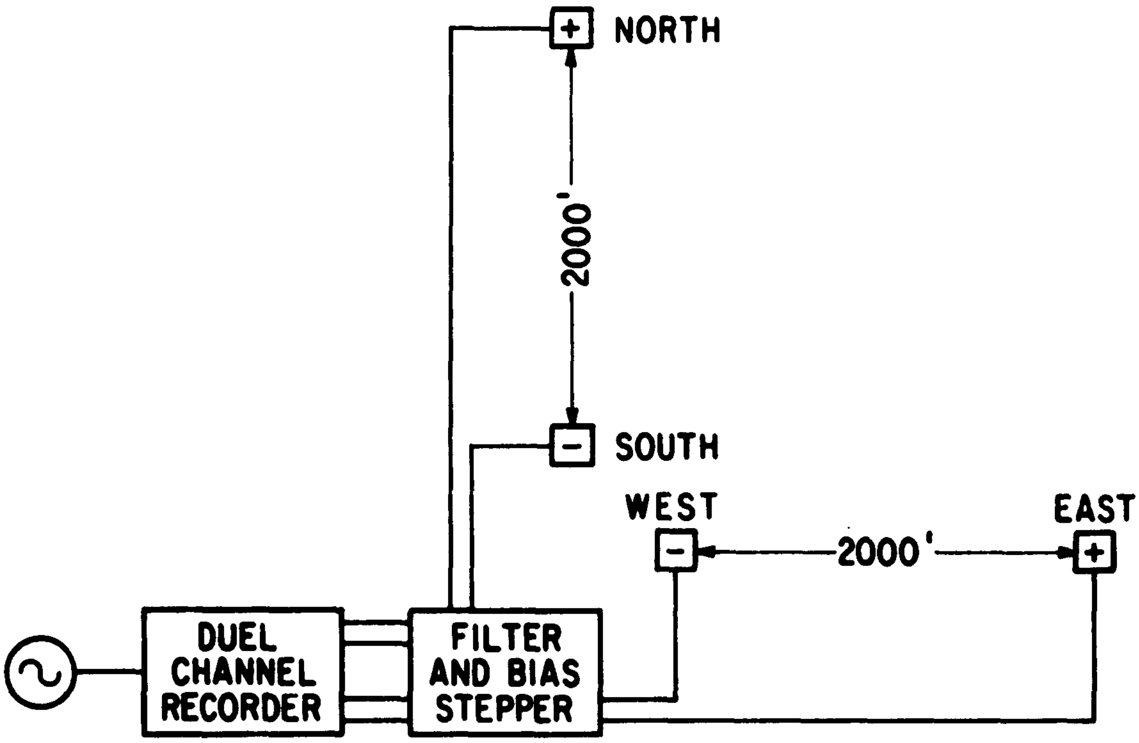


+ POSITIVELY SENSED ELECTRODE

− NEGATIVELY SENSED ELECTRODE

FIG. I SCHEMATIC OF EARTH CURRENT STATION LAYOUT

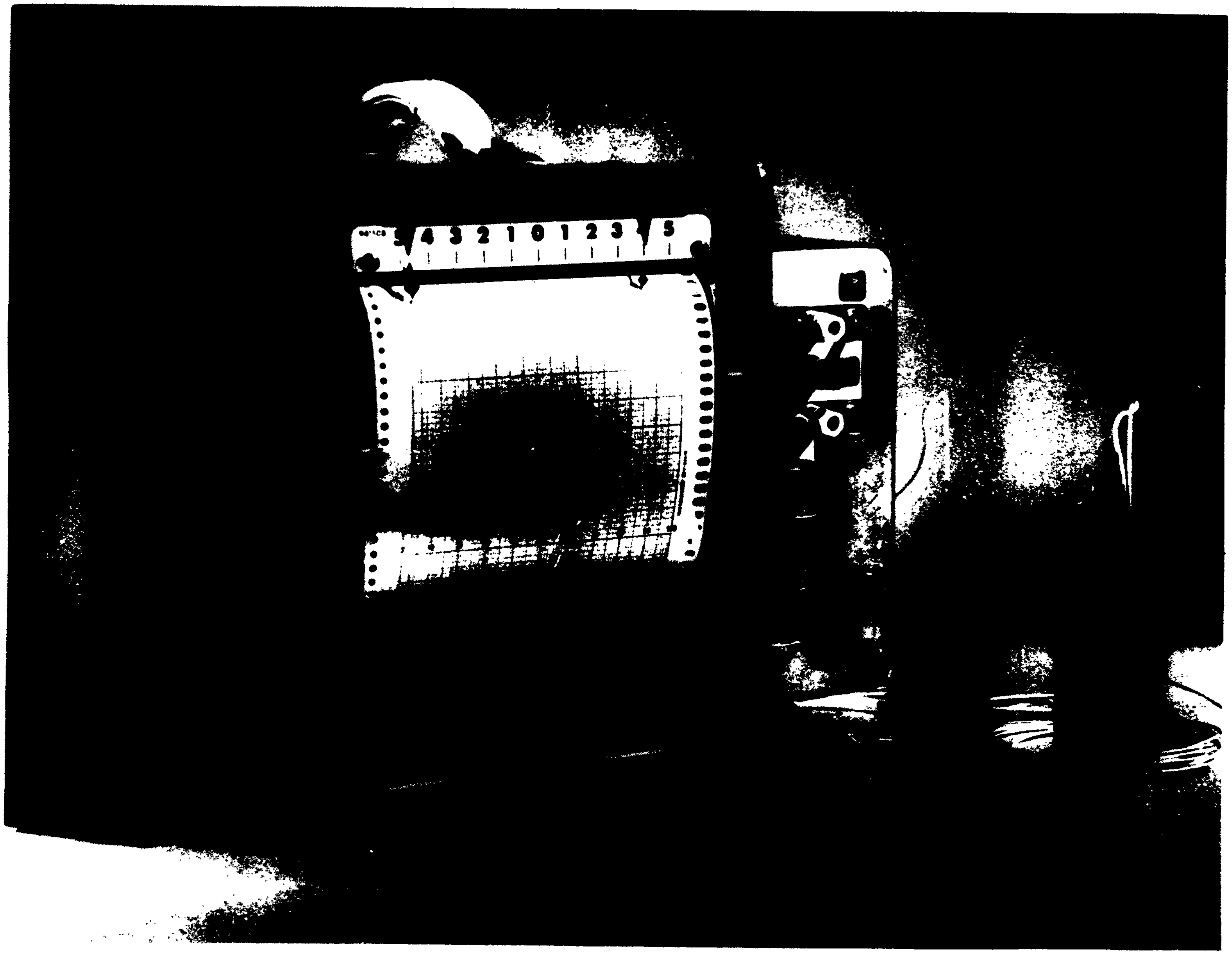


Figure 2. Photograph of Earth Current Unit

Figure 3. Photograph of Filter and Bias-Stepper Layout

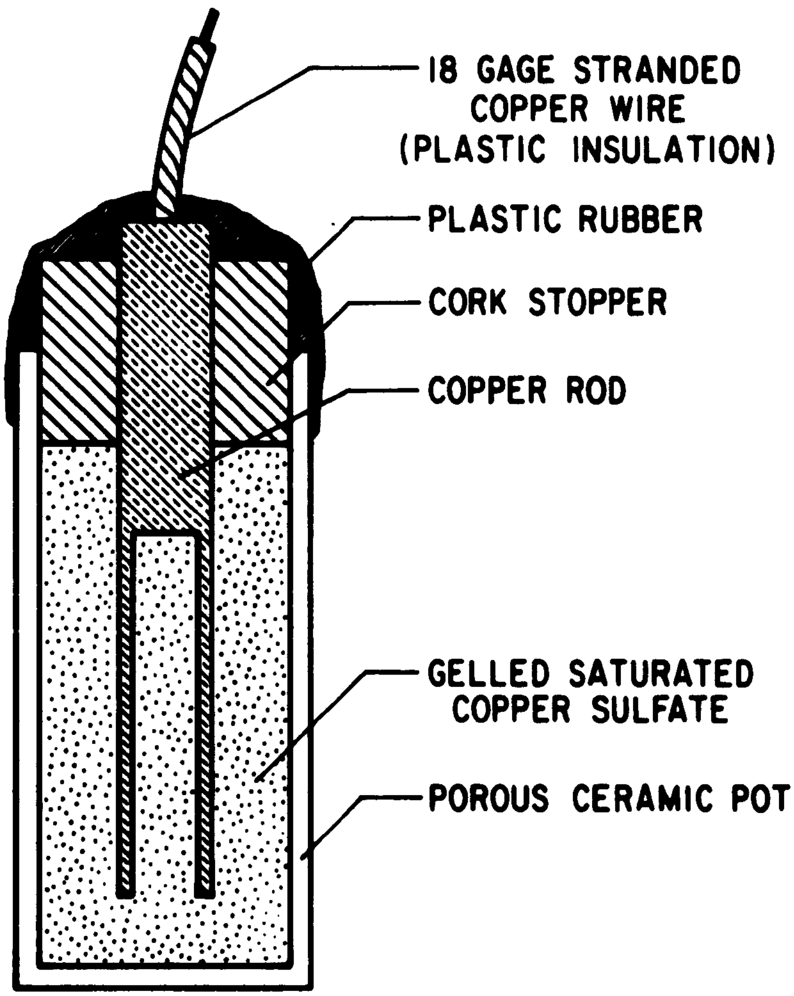
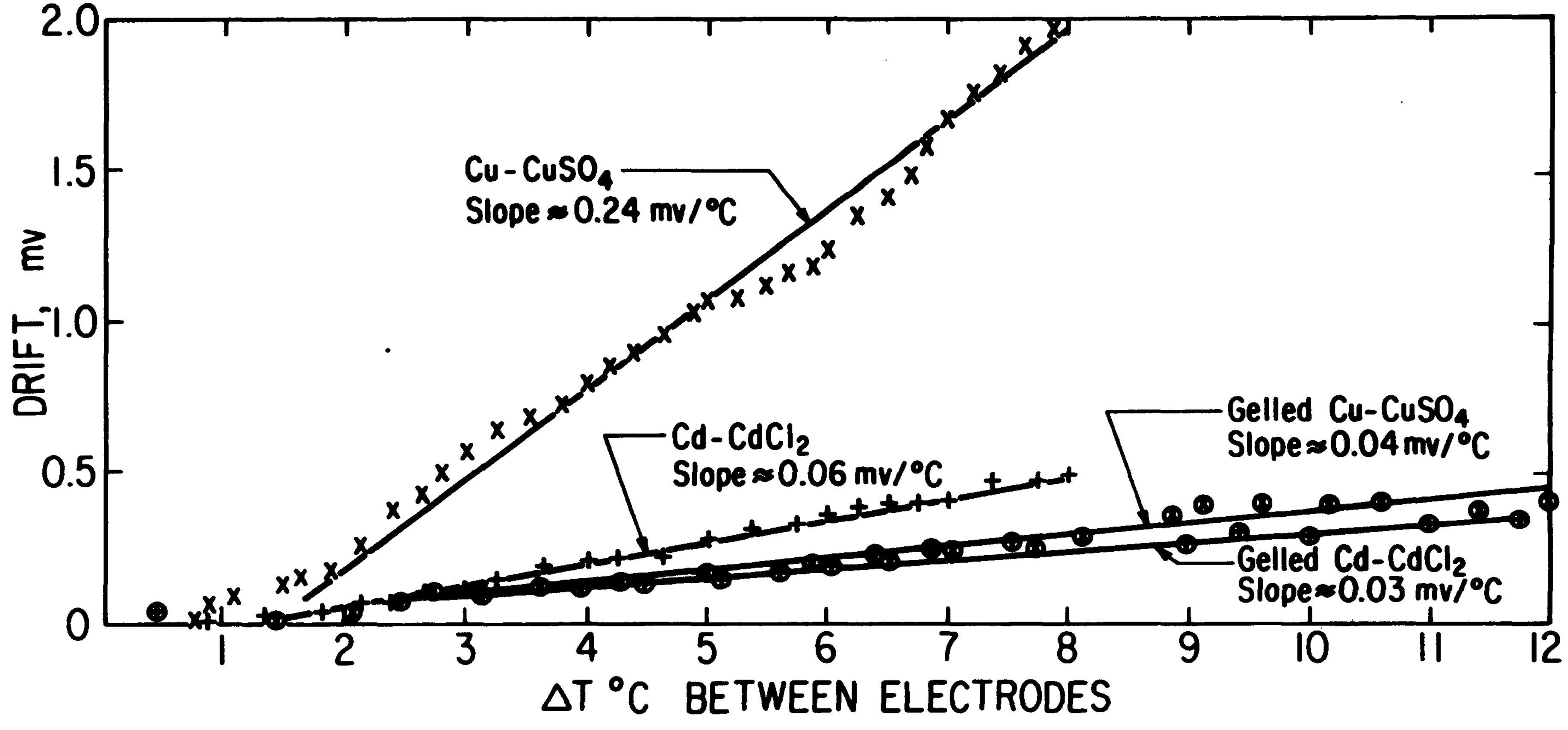


FIG. 4 CROSS-SECTION OF NON-POLARIZABLE ELECTRODE



READING ACCURACY OF THERMOMETER ± 0.1°

FIG. 5 TEMPERATURE DRIFT-SOLUTIONS AND GELS IN ICE-BATH ENVIRONMENTS
JUNE 20, 1961

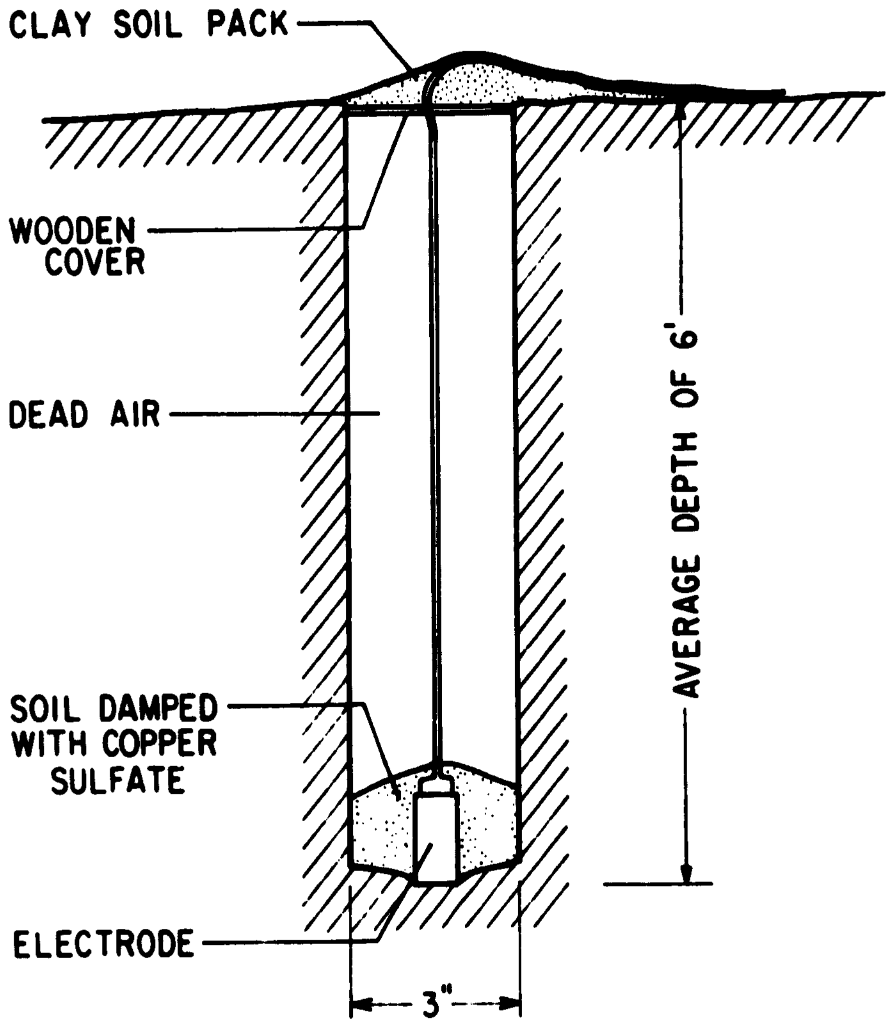


FIG. 6 FIELD PLACEMENT OF ELECTRODES TO EFFECT THERMAL AND MOISTURE STABILITY

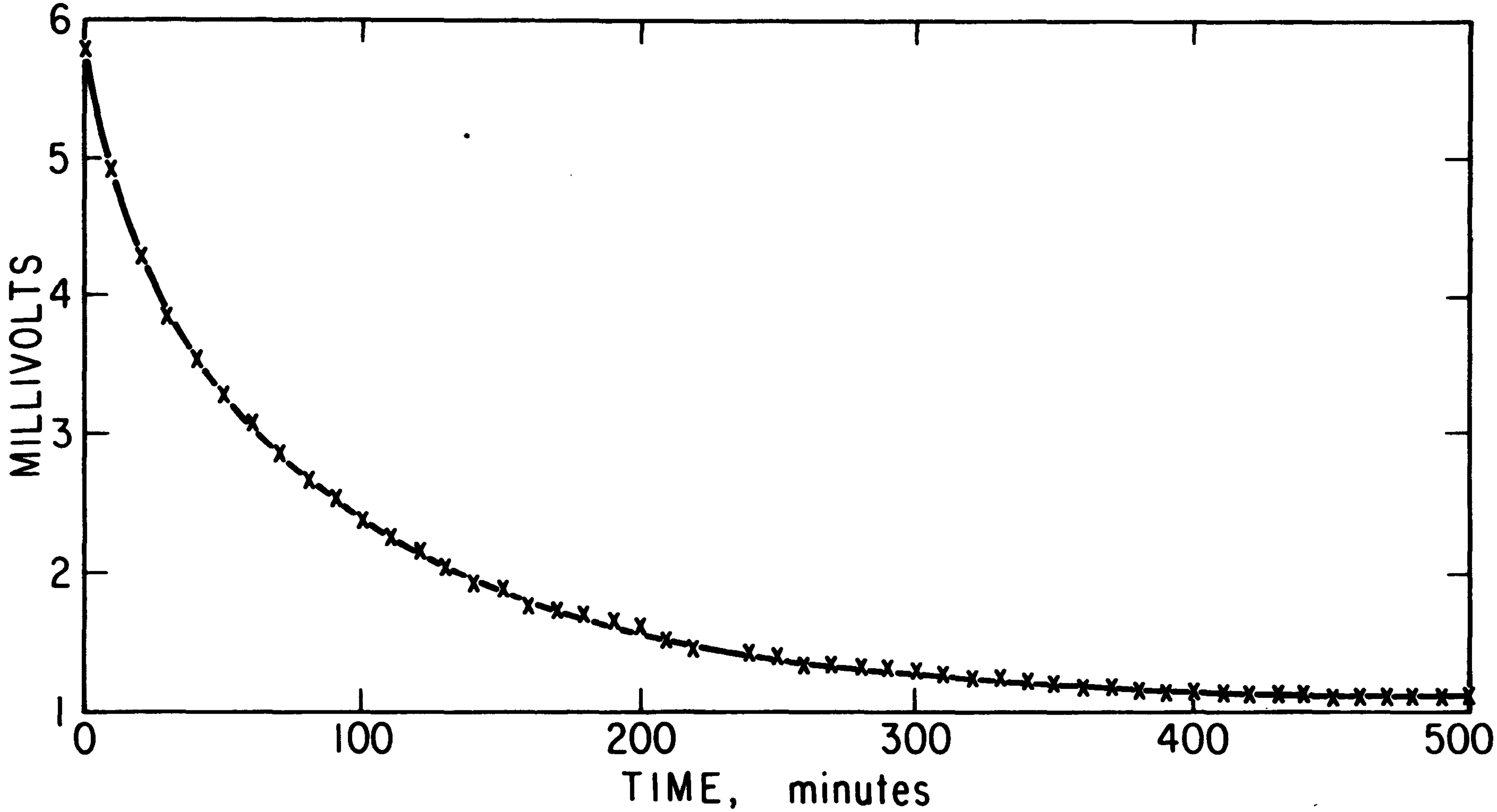


FIG. 7 STABILITY CURVE OF GELLED $Cu-CuSO_4$ ELECTRODES IN SILICA SAND

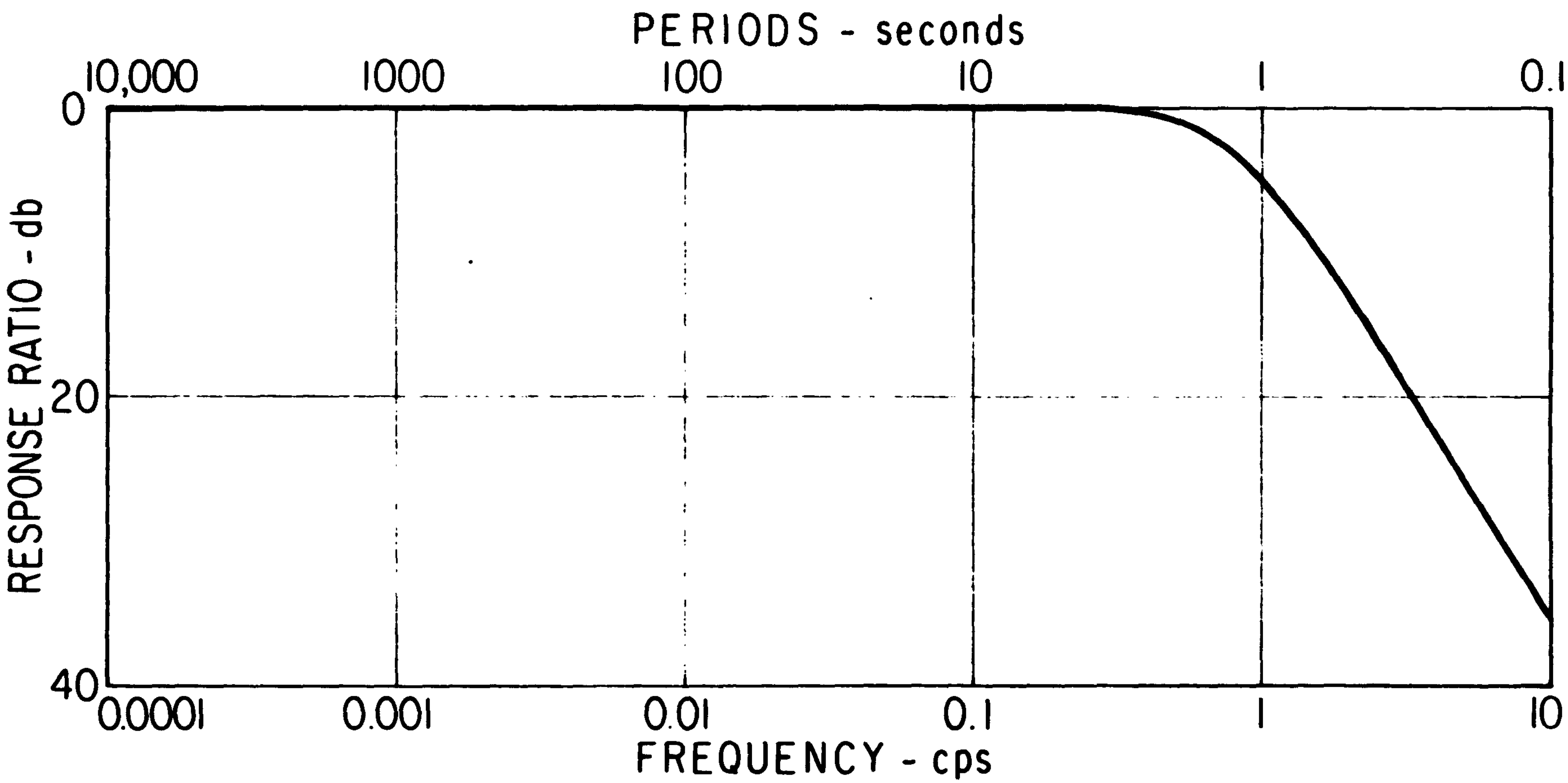


FIG. 8 FREQUENCY RESPONSE OF EARTH CURRENT SYSTEM

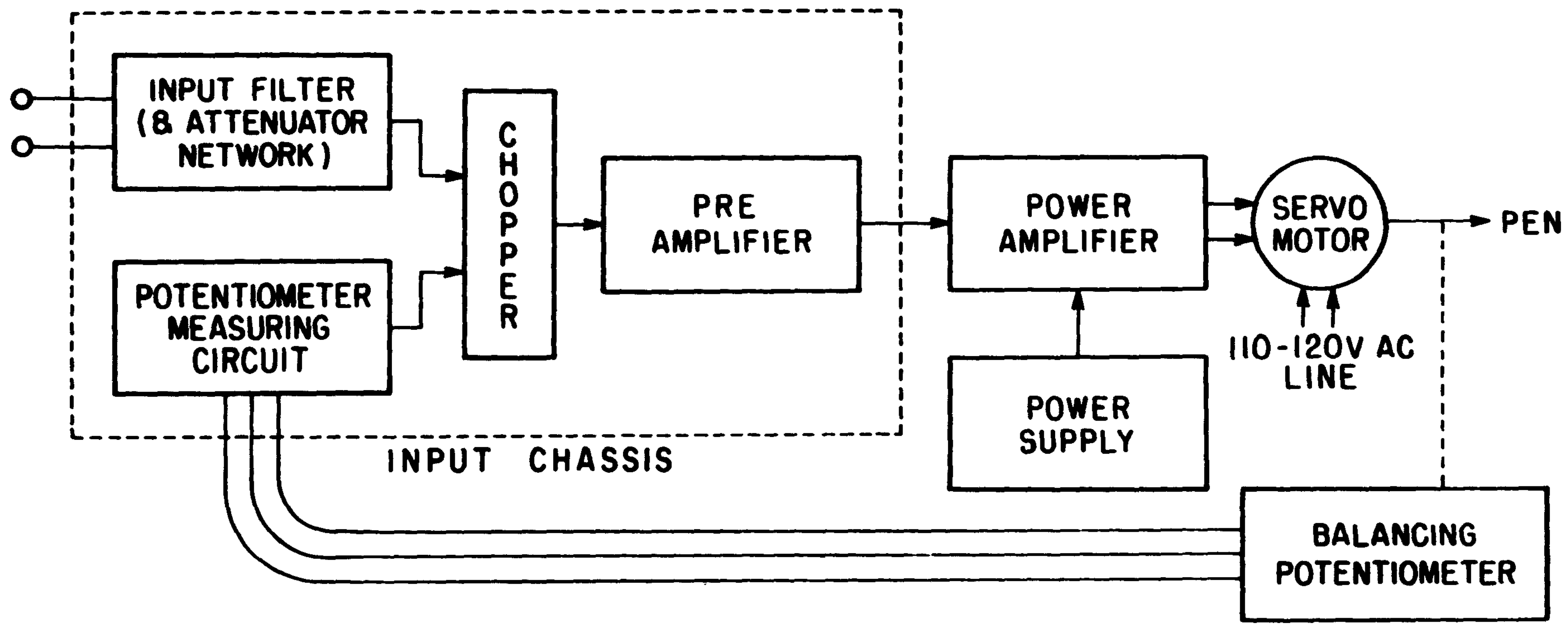
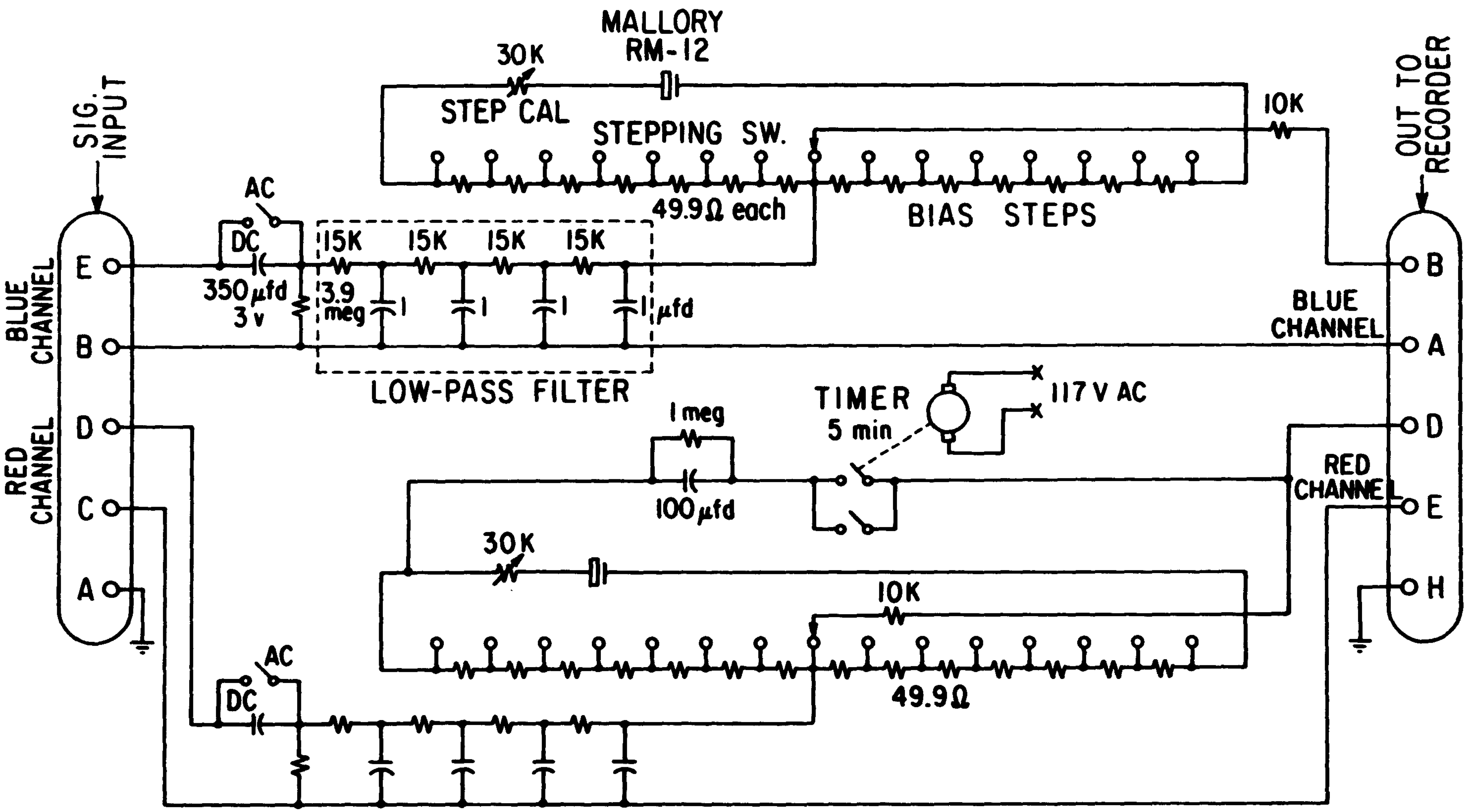


FIG. 9 BLOCK DIAGRAM OF VARIAN G-22 RECORDER



49.9Ω RESISTORS
SPRAGUE 429E49R9F

STEPPING SW.
GUARDIAN IR-RAS-12

CHANNELS IDENTICAL EXCEPT FOR TIMER ON RED CHANNEL

FIG. 10 SCHEMATIC OF BIAS CIRCUIT

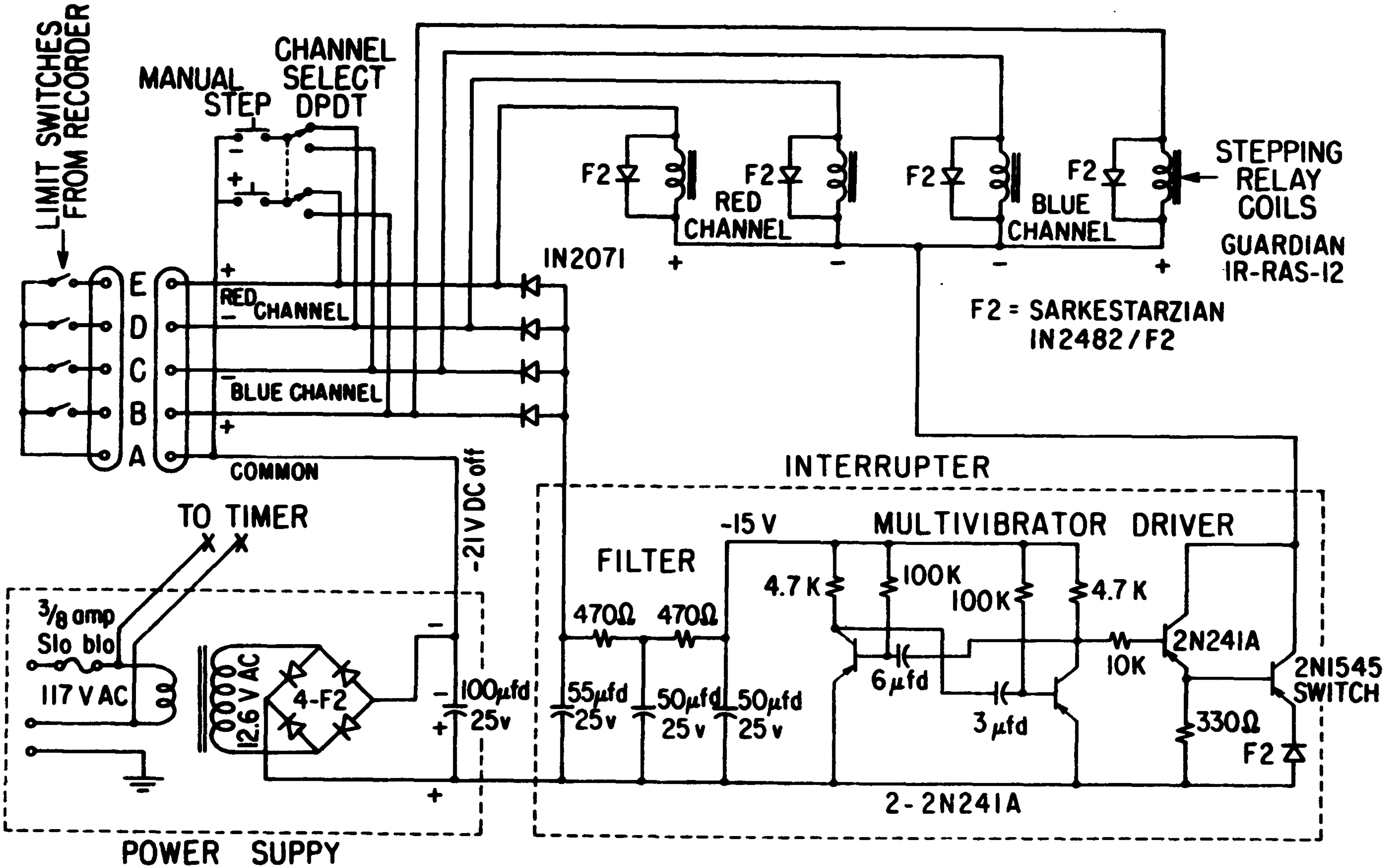


FIG. 11 SCHEMATIC OF STEPPING CIRCUIT

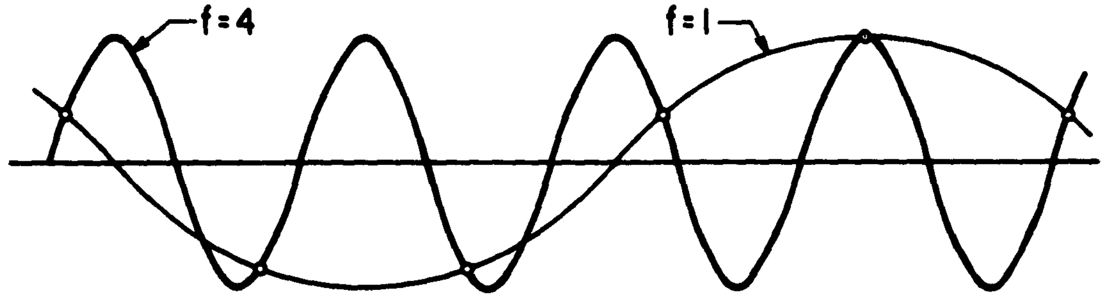


FIG. 12 ALIASING OF HIGH FREQUENCY (f=4) AS LOW FREQUENCY (f=1) DUE TO INADEQUATE SAMPLING INTERVAL

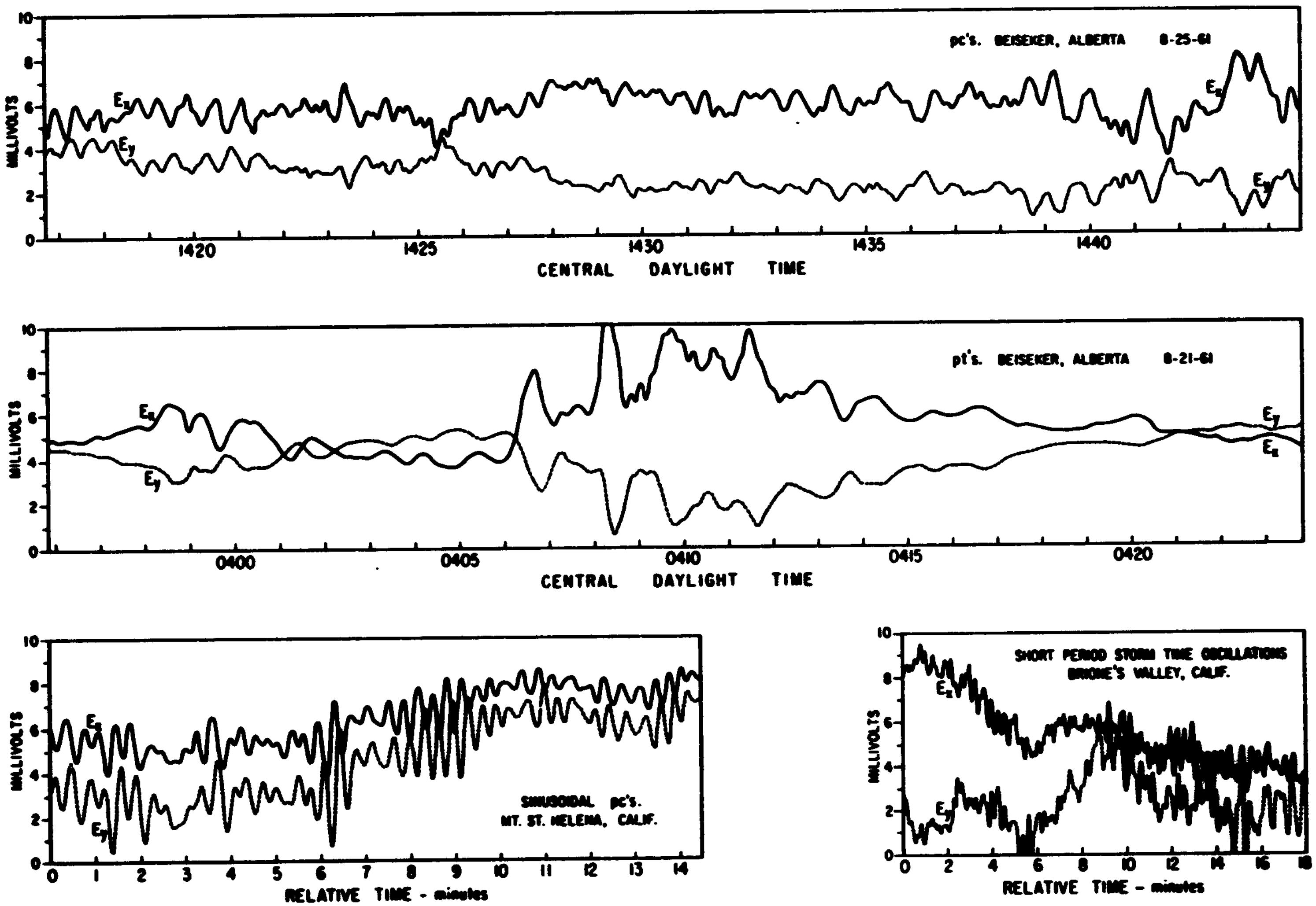


FIG. 13 TYPICAL EXAMPLES OF EARTH CURRENT DATA